

Tutorial 4.1 — Basics of Radiation Interactions with Matter

Slide 1. Basics of Radiation Interactions with Matter

Analysis of alpha and beta emitting radionuclides depend on the ways that these particles interact with matter. This session explores those mechanisms and the techniques used to detect these interactions.

Slide 2. Learning Objectives

At the end of this lesson you should be able to:

- Explain the different ways that alpha and beta particles interact with matter.
- Identify the type(s) of detector that are useful for alpha and beta detection and how the interactions with matter provide a better response in one instrument over another.
- Describe the three ways that gamma rays interact with matter that is important in gamma ray spectrometry.
- State which gamma ray interactions lead to the three specific features in the gamma ray spectra identified as —
 - full energy peaks,
 - Compton continuums, and
 - annihilation peaks.
- Define the terms “decay scheme” and “fractional abundance factor” and describe their importance in gamma ray spectrometry.

The key concepts to be gleaned from this lesson are:

- The final choice of detector type depends on the energy of the particles being detected and on the instrumentation available to the laboratory.
- The only gamma ray interaction that provides valuable information for quantitation of a radionuclide is the photoelectric effect.
- To accurately measure the activity of radionuclides, the abundance factor needs to appear in the equation for determining activity.

Slide 3. How Are Radioactive Decay Particles Detected?

The instrumentation that is commonly used in the radiochemistry laboratory detects radioactive particles based on the way they interact with electrons in the matter that makes up the detection system. The physical parameter that actually is measured is directly proportional to the amount of energy transferred to an electron or electrons, and that is then converted into a signal that the analyst can use to quantitate the amount of radioactivity present.

In liquid scintillation all three types of radiation, alpha, beta and gamma, cause excitation of electrons in solvent molecules. This excitation energy is transferred to a fluor molecule which de-excites yielding a photon of energy in a distinct range that is detected by a conventional photomultiplier tube.

When alpha particles interact within a silicon or germanium detector or with the P-10 gas in the proportional counter, we rely on the alpha particle creating many ionized atoms, the electrons liberated in these processes leading to the measured signal. The number of electrons liberated in the formation of the ion pairs is directly related to the incident alpha particle energy.

Gamma rays are detected as a result of their ionization of matter, liberating electrons from K-shells of atoms. One electron is liberated for each gamma ray and thus that electron kinetic energy contains the energy proportional to the incident gamma ray.

Slide 4. Why It's Important?

So why is it so important to know how the radiation interacts with matter? After all once the instrument is calibrated doesn't it always give us the right answers? NO. The preparation of the sample test source and knowing the possible materials that may contaminate the sample test source are very important in determining how the decay particles will interact with the detecting medium. Understanding how these interactions occur will also allow us to examine spectra and assess whether or not a spectral or physical interference is occurring. If we know that there is an interference we may be able to account for it either in sample preparation or spectral analysis, providing us with the most accurate result.

Slide 5. Alpha Particles – Ionization

The picture on the right displays the primary means by which alpha particles interact with matter. Their high kinetic energy, positive charge and large mass compared to an electron, allows them to cause a great many ionizations in a very short travel distance. Alpha particles will create about 10^5 ion pairs before they come to rest and become neutral atoms. The ionization interactions occur with the weakest held electrons which are the valence electrons. These are the interactions we rely upon for detection with the gas proportional counter.

Slide 6. Alpha Particles – Excitation

Similar to the interaction of alpha particles causing ionization is the interaction of excitation. Here the alpha particle imparts enough attractive force to raise an electron up from a lower to a higher energy state in the same atom. This is an important transfer mechanism in liquid scintillation analysis.

Slide 7. Beta Particles - Ionization

Beta particles have about one-eight thousandth the mass of an alpha particle. Thus for each interaction they have, they lose a significantly greater amount of energy. Beta particles will form between about one hundred and ten thousand ion pairs before they are captured by an atom. Their interactions are by coulombic repulsion and also occur with valence shell electrons. These are the interactions we rely on for response in the gas proportional counter. The number of ion pairs produced by a beta particle is significantly less than those produced by an alpha particle.

Slide 8. Beta Particles – Excitation

Just like alpha particles, if the beta does not transfer enough energy to the electron it will not be ionized but excited to a higher energy level within the same atom. This is the interaction that we rely on in liquid scintillation analysis.

Slide 9. Beta Particles – Bremsstrahlung Radiation

Finally beta particles can interact with matter in a third way. As the beta particle approaches an atom it can interact with the nucleus by attraction. This attraction would slow down the beta particle causing it to radiate a continuous low level stream of photons as the beta particle

decelerates. For radiochemical analyses this type of interaction is not useful. In fact in gamma spectrometry it is actually a detriment as it will raise the general background in the spectrum.

Slide 10. Path Length in Matter

Beta and alpha particles have different path lengths in matter based on the interactions described above. The denser the matter they travel through is, the greater the number of electrons there will be and the greater the number of interactions per linear unit will occur. Thus, more interactions lead to a shorter travel length.

Slide 11. Summary of Alpha and Beta particle Detection

The table on this slide summarizes the manner in which alpha and beta particles interact in the instrument that is used to detect these particles. Both ionization and excitation occur during each decay, but the type of detector used governs which interaction is measured.

Slide 12. Interactions of Gamma Radiation with Matter

Gamma rays are massless, chargeless quanta of energy. The range of energy that we are interested in when we analyze a sample by gamma spectrometry is from about 10 to about 3,000 keV. Gamma rays don't create ion pairs in matter by the coulomb effect like alpha and beta particles do, but because of their physical properties as quanta of energy they will interact mainly with K-Shell electrons. The two interactions that occur in this manner are the photoelectric effect and the Compton Effect. Gamma rays interact with matter in one other way that affects gamma spectrometry analysis and that is by the pair production effect. We will now discuss how these interactions occur and what we see as a result of these interactions in the gamma ray spectrum.

Slide 13. Gamma Ray Ionization via the Photoelectric Effect

In this effect the incoming gamma ray transfers 100% of its energy to ejecting a K-shell electron from the atom. The electron has a small binding energy, but it is negligible compared to the energy range of gamma rays that are determined in routine gamma ray analysis. When a gamma ray interacts by this mechanism, the free electron produced will have a kinetic energy that is a direct measure of the incident gamma ray energy. This interaction produces the feature in the gamma ray spectrum that we call the full energy peak, or FEP. The FEP is unique for a specific radionuclide.

Slide 14. Gamma Ray Ionization via the Compton Effect

When a gamma ray only transfers some of its energy to a bound K-shell electron, there are a variety of different scattering angles that the electron and gamma ray can have. Thus there is not a unique gamma ray energy associated with the Compton Effect. The equation shown on this slide is derived from the unique physical interactions of photons with particles. What it says is that there is a minimum energy with which a gamma ray can be scattered- below that point there is either no interaction or the interaction occurs via the photoelectric effect. This means that the other half of this interaction, the scattered electron, has a maximum to its possible energy. When this effect occurs in the germanium detector this scattered electron of maximum energy is a distinctive feature of the gamma ray spectrum called the Compton Edge.

Slide 15. Pair Production and Annihilation (first of four slides)

The gamma ray interactions discussed in the previous slides resulted in direct ionization of the absorbing medium. The third effect that gamma rays can have that is important in gamma ray spectrometry is called the pair production effect. The incident gamma ray of a certain minimum energy interacts with the coulombic field of the nucleus and degrades into two particles; one of matter and one of anti-matter. The minimum energy required is 1.022 MeV, and the two particles formed are a negatron and a positron. The reason that this is the minimum energy for this to occur is based on the Einstein equation, $E = mc^2$. If we substitute the rest mass of an electron and the speed of light into this equation, and add the appropriate conversion factors we find that the energy equivalent of an electron's rest mass is 0.511 MeV. Since a positron has the same rest mass as an electron, the gamma ray will need 2 times 0.511 MeV or 1.022 MeV of energy in order for the pair production effect to occur.

Slide 16. Pair Production and Annihilation (second of four slides)

The processes of pair production can occur when a gamma ray of energy 1.022 MeV interacts with the coulombic field of the nucleus. The picture on the right shows the transformation that occurs. If the gamma had exactly 1.022 MeV of energy, a positron and a negatron would be formed and there would be no energy left over. Theoretically the particles would be motionless. The positron would immediately undergo annihilation with an electron, yielding two 0.511 MeV photons.

The actual energy of the gamma ray has to be slightly greater than 1.022 MeV since the nucleus must absorb some energy in order to conserve momentum.

Slide 17. Pair Production and Annihilation (third of four slides)

When the gamma ray has more than the 1.022 MeV of energy required to cause pair production and provide sufficient energy for the conservation of momentum, the "left over" energy is split almost evenly between the positron and the negatron as kinetic energy. The negatron migrates as it normally would in matter, and the positron migrates a very short distance and very short time before it pairs with an electron and begins to spiral together toward annihilation.

Slide 18. Pair Production and Annihilation (fourth of four slides)

During the process of spiraling together prior to annihilation, the positron slows down via attraction to that electron. When this happens the positron radiates its kinetic energy as low energy photons. When the kinetic energy is almost zero, the positron and electron collapse together and annihilate yielding the two 0.511 MeV photons.

Slide 19. Detector Interactions for Gamma Rays

In the previous slides of this tutorial, we described the three different types of gamma ray interactions that can occur with matter. When any of these occur within the detector, we will get a signal that leads to a feature in the gamma ray spectrum. A single gamma ray will have a single interaction within the detector, and this interaction is both dependent upon the gamma ray energy and the atomic number of the absorbing detector material.

For high purity germanium detectors, the photoelectric effect is the dominant form of interaction up to about 140 keV. From that point up to about 3,000 keV the Compton Effect is the dominant

interaction of the gamma rays with the detector. Keep in mind that the only interaction that leads to the full energy peak in the gamma ray spectrum is the photoelectric effect. The full-energy peak is the one that may be used for quantitation of the radionuclide activity.

Slide 20. Gamma Ray Interactions Outside the Detector

It is important to remember that our sample containing radionuclides will emit gamma rays equally in all directions. Since our detectors usually have a maximum intercept arc for the emitted gamma rays of 180° (that would make them a maximum of 50% efficient), many of the emitted gamma rays interact with materials other than the detector.

The table on this slide identifies some of the most common effects that occur outside the detector and what the effect is *on the detector* when this occurs. Keep in mind that once the interaction outside the detector occurs the resultant photons from that interaction are also emitted equally in all directions. That means that some are directed back towards the detector and can interact via the photoelectric effect.

Slide 21. Decay Schemes

A Decay Scheme is a pictorial representation of the particle and energy transformation in the nucleus when it undergoes radioactive decay. As an example a radioactive nuclide that has excess neutrons will emit a negatron so that a neutron within the nucleus is converted to a proton. In doing so the nucleus may be left in an excited state. The nucleus may then de-excite to a ground state by emitting electromagnetic radiation in the form of gamma rays or x-rays; the x-rays being produced by the internal conversion process.

Slide 22. Simplified ^{60}Co Decay Scheme

The picture on the right is an example of a simple decay scheme for ^{60}Co . Co-60 emits a negatron of 0.31 MeV and the resultant nucleus of ^{60}Ni is in an excited state that has “extra” energy of 2.505 MeV. The nucleus de-excites from this energy level in two steps – the first it emits a 1.17 MeV gamma ray going to a slightly lower energy state, then that energy state emits gamma radiation and the ^{60}Ni nucleus goes to the ground state. For almost every 1.33 MeV gamma that comes from the 0.31 MeV negatron decay, we also will get a 1.17 MeV gamma ray.

Slide 23. Decay Schemes and Branching Ratios

The picture on this slide shows the more complete decay scheme for ^{60}Co . In addition to the negatron decay of 0.318 MeV, it can also decay by emitting a higher energy negatron of 1.492 MeV that leaves the nucleus in the lower excited state of 1.33 MeV. This scheme also shows that there can be de-excitation directly from the 2.505 MeV state to the ground state.

Also shown in this scheme are the appropriate branching ratios when a de-excitation or decay mode is split. Thus the 318 keV beta is emitted 99.88 % of the time and the 1492 keV beta only 0.12 % of the time.

Slide 24. Significance of Branching Ratios

If we use the decay scheme we can determine how many gamma rays on average will be produced from the decay of a radionuclide. For Co-60 every 10,000 decays will yield 9,988 beta

particles that leave the progeny in the 2.505 MeV excited state. From that excited state, only 99.97 yield a gamma ray of 1.17 MeV. Thus for each 10,000 decays of Co-60 there will be,
 $0.9979 \times 9,988 = 9,967$ gamma rays emitted of energy 1.17 MeV.

This value of 9967/10000 is called the *branching ratio* or the *fractional abundance factor*.

Slide 25. Correcting for Fractional Abundance

The decay scheme for Cs-137 is shown on the right side of this slide. For Cs-137 it emits a beta of 0.514 MeV 94.4 % of the time. The only excited state of Ba-137 is the 0.661 MeV level, and this de-excites directly to ground state. Note that adjacent to the arrow going to the ground state that the abundance for that gamma ray is only 85.1 %. What happens to the other 9.3 % of the excited states? The nucleus undergoes de-excitation by transferring all the excited state energy to a k-shell electron which is ejected from the sphere of influence of the atom. This energy transfer results in the emission of barium x-rays at ~30 keV. However we don't observe these x-rays in our gamma ray spectrum since we usually only measure down to about 50 keV.

Slide 26. Conclusion

In this module we have discussed the way that alpha, beta, and gamma particles interact with matter.

You should be able to describe each of the two interactions for alphas and the three interactions for beta and gamma rays. Additionally you should be able to identify the specific type of interaction that is used for the different types of detectors used to measure these emissions.

Finally, the decays schemes of two radionuclides were shown. From schemes like these you should be able to calculate the fractional abundance for gamma ray emission.